The Little Neutral One

A brief introduction to neutrinos

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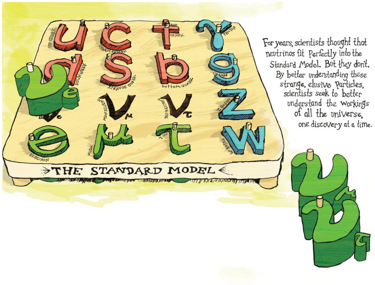
About Neutrinos



From Symmetry Magazine, Feb 2013

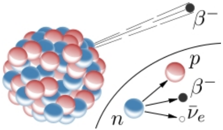
Cosmic Gall

by John Updike

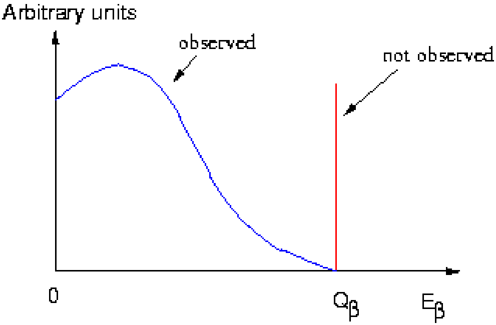
Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.

A BRIEF HISTORY OF THE NEUTRINO

Neutrino Conception



Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

.........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant..........
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant

. W. Pauli

Neutrino Conception

The Little Neutral One

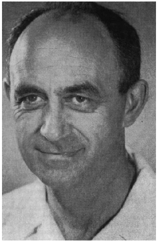
Mary Bishai Brookhaven National Laboratory

1932: James Chadwick discovers the neutron, $\text{mass}_{\text{neutron}} = 1.0014 \times \text{mass}_{\text{proton}}$ - its too heavy - cant be Pauli's particle

James Chadwick

Neutrino Conception

Solvay Conference, Bruxelles 1933: Enrico Fermi proposes to name Pauli's particle the "neutrino".

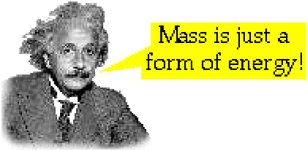


Enrico Fermi

Particle physics units and symbols

Symbols used for some common particles:

Symbol	Particle
ν	Neutrino
γ	Photon
e^-	Electron
e^+	Anti-electron (positron)
p	proton
n	neutron
N	nucleon - proton or neutron



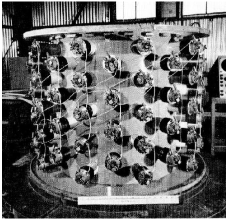
Particle physicists express masses in terms of energy, mass $= E/c^2$, mass$_{proton}$ $= 1.67 \times 10^{-24}$g $\approx 1 \times 10^9$ electron-volts $= 1\text{GeV}/c^2$

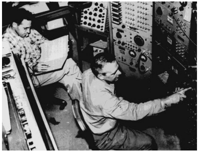
Finding Neutrinos...

1950's: Fred Reines at Los Alamos and Clyde Cowan use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.

The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$
3. $n +^{108} Cd \rightarrow^{109} Cd* \rightarrow^{109} Cd + \gamma$ $(\tau = 5\mu s)$.





Neutrinos first detected using a nuclear reactor!

ν: A Truly Elusive Particle!

Reines and Cowan were the first to estimate the interaction strength of neutrinos.

The cross-section is $\sigma \sim 10^{-43}\mathrm{cm}^2$ per nucleon (p,n).

$$\nu \text{ mean free path} = \frac{\text{Mass of the proton}}{\sigma \times \text{density}}$$

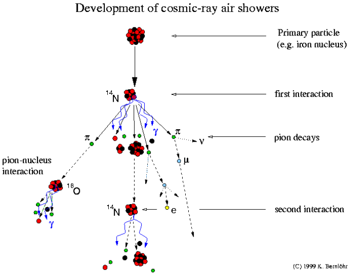
$$= \frac{1.67 \times 10^{-24}\mathrm{g}}{10^{-43}\mathrm{cm}^2 \times 11.4\mathrm{g/cm}^3} \approx 1.5 \times 10^{16}\mathrm{m} = \textbf{1.6 LIGHT YEARS}$$

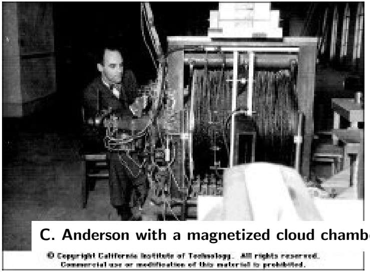
A proton has a mean free path of 10cm in lead

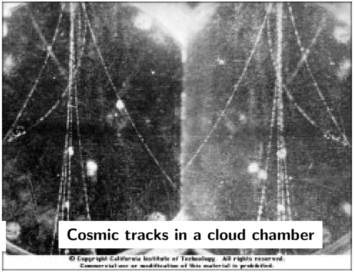
Neutrino detectors have to be MASSIVE

Discovery of the Muon (μ)

1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).




C. Anderson with a magnetized cloud chamber


Cosmic tracks in a cloud chamber

The Lepton Family and Flavors

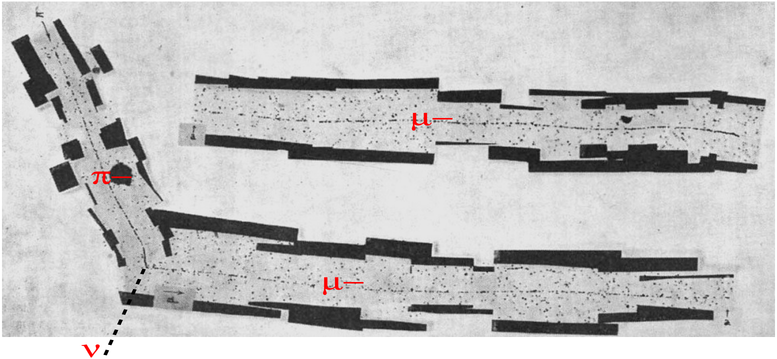
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons***.**

Generation	I	II	III
Lepton	e^-	μ	τ
Mass (GeV)	0.000511	0.1057	1.78
Lifetime (sec)	stable	2.2×10^{-6}	2.9×10^{-13}

Neutrinos are neutral leptons. **Do ν's have flavor too?**

Discovery of the Pion: 1947

Cecil Powell takes emulsion photos aboard high altitude RAF flights. A charged particle is found decaying to a muon:

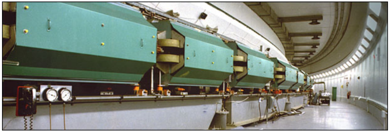


$\text{mass}_{\pi^-} = 0.1396\ \text{GeV}/c^2$, $\tau = 26$ ns.

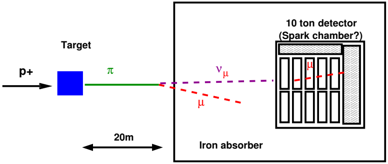
Pions are composite particles from the "hadron" family which includes protons and neutrons.

Neutrinos have Flavors

1962: **Leon Lederman, Melvin Schwartz and Jack Steinberger** **use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu\nu_x$**



The AGS



Making ν's

Result: **40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$**

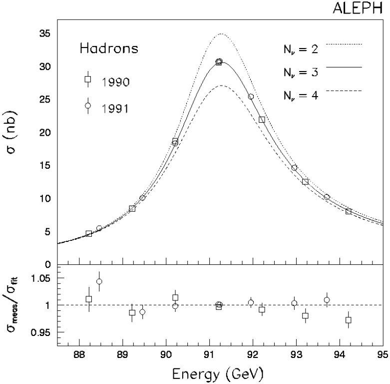
The first accelerator neutrino experiment was at the AGS.

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: **The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.**

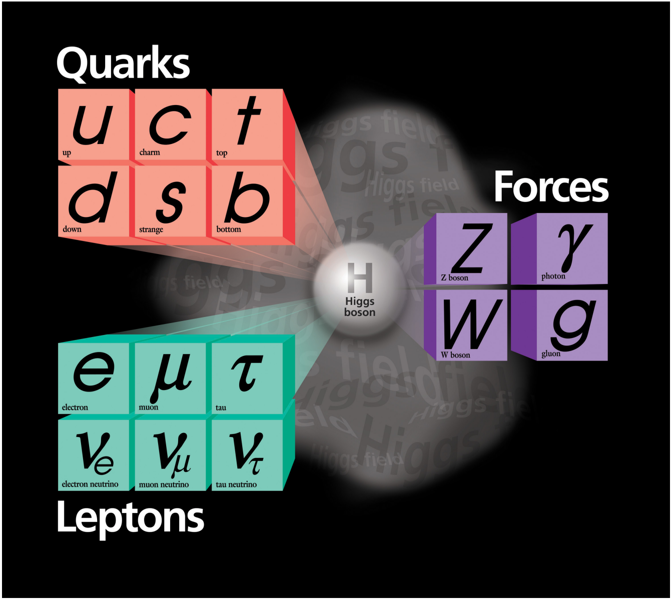
The LEP e^+e^- collider at CERN, Switzerland

The 27km LEP ring was reused to build the Large Hadron Collider



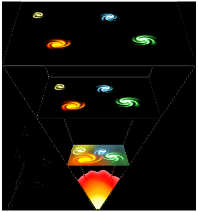
$$N_\nu = 2.984 \pm 0.008$$

The Particle Zoo



Sources of Neutrinos

Big Bang

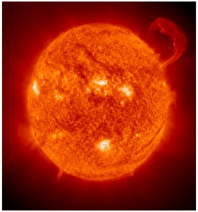


10^{-4} eV
300/cm^3

Reactors

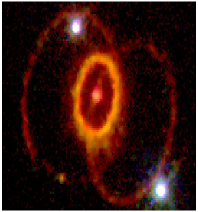
few MeV
10^{21}/GW$_{th}$/s

Sun



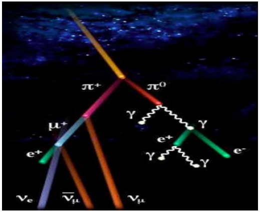
0.1-14 MeV
10^{10}/cm^2/s

SuperNova



$\sim$ 10 MeV
10^9/cm^2/s

Atmosphere

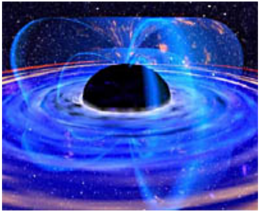


$\sim$ 1 GeV
few/cm^2/s

Accelerators

1-20 GeV
10^5/cm^2/s (at 1km)

Extragalactic



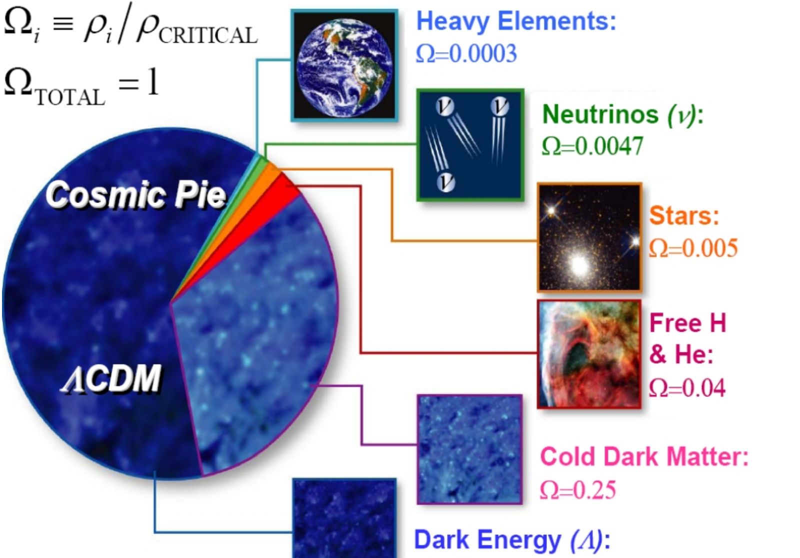
TeV-PeV
varies

Neutrinos and Todays Universe

Neutrino mass $<$ 2 eV (beta-decay limits)

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$



NEUTRINO MIXING AND OSCILLATIONS

Some Quantum Mechanics

1924: Louis-Victor-Pierre-Raymond, 7th duc de Broglie proposes in his doctoral thesis that all matter has wave-like and particle-like properties.

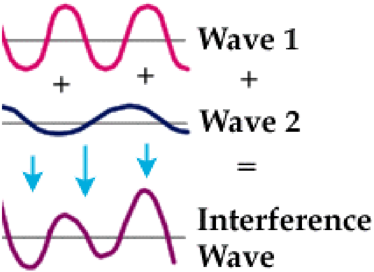
For highly relativistic particles : energy ≈ momentum

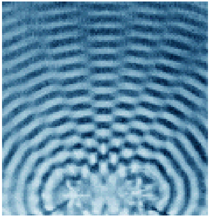
De Broglie

$$\text{Wavelength (nm)} \approx \frac{1.24 \times 10^{-6}\ \text{GeV.nm}}{\text{Energy (GeV)}}$$

Neutrino Mixing

1957,1967: B. Pontecorvo proposes that neutrinos of a particular flavor are a mix of quantum states with different masses that propagate with different phases:



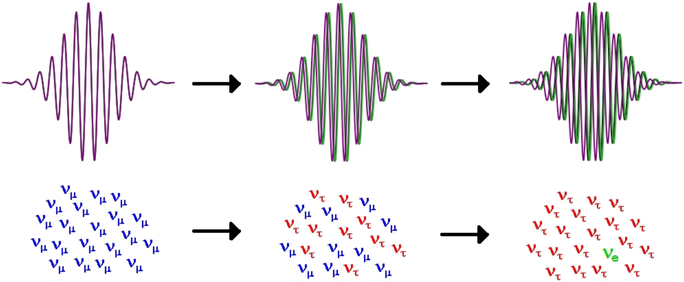


The interference of water waves coming from two sources.

The inteference pattern depends on the difference in masses

Neutrino Oscillations

Neutrino mass states *interfere* $\Rightarrow$ neutrinos oscillate between different flavors:



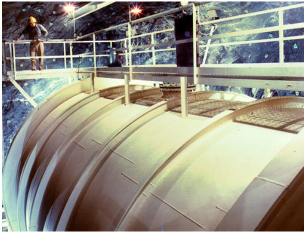
If neutrinos oscillate $\Rightarrow$ neutrinos have mass!

The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

Ray Davis

1. $\nu_e^{sun} + ^{37}CL \rightarrow e^- + ^{37}Ar$, $\tau(^{37}Ar) = 35$ days.
2. Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.



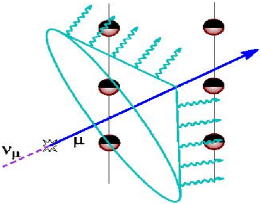
Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Solar ν_e disappearance $\Rightarrow$

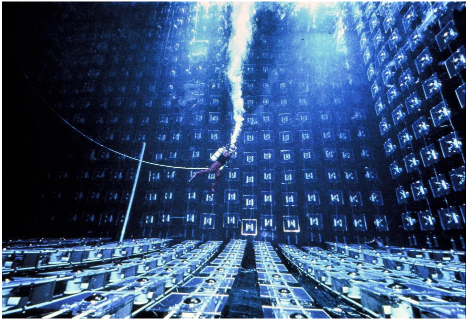
first experimental hint of oscillations

Water Cerenkov Neutrino Detectors

A relativistic charged particle going through water, produces a ring of light

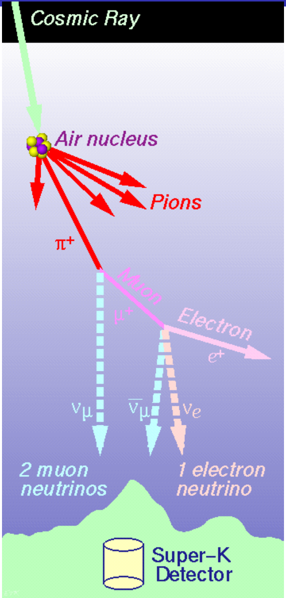


The Irvine-Michigan-Brookhaven Detector

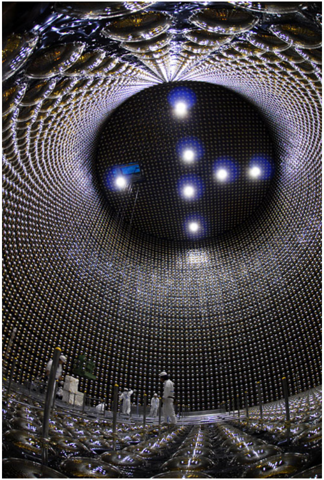


With water, get MASSIVE detectors (kilo-tons)

The Super-Kamiokande Detector Mount Ikena, Kamioka, Japan



A huge 50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.



Identifying ν_μ and ν_e Interactions

$\nu_e + N \rightarrow e^- N'$ $\qquad$ $\nu_\mu + N \rightarrow \mu^- N'$

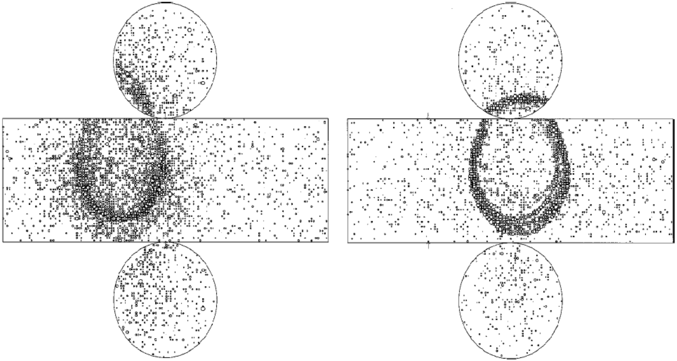
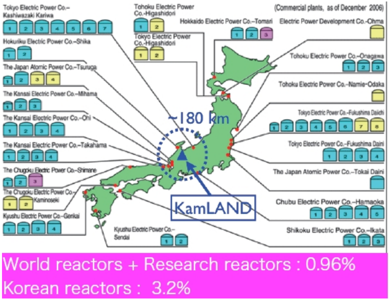
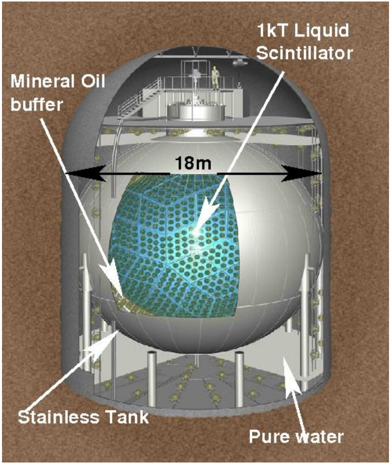


FIG. 24. An e-like (left) and a μ-like (right) event observed in the Super-Kamiokande detector.

KamLAND: Reactor $\bar{\nu}_e$ Detector Kamioka Mine

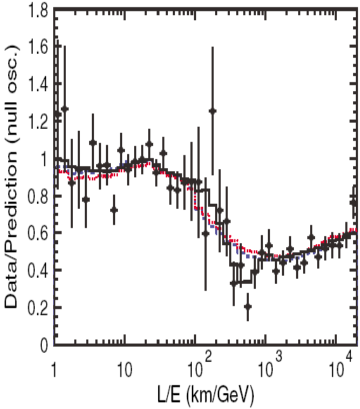
Japan's electric power is mostly from nuclear reactors, the Kamioka Mine is bombarded by $\bar{\nu}_e$ from reactors:



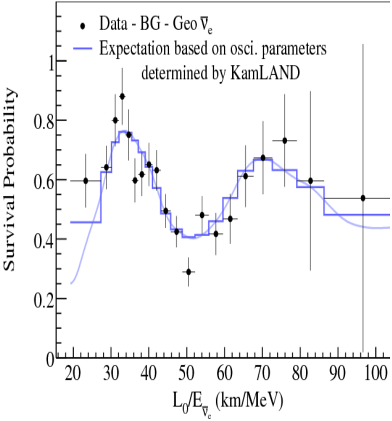


Neutrino Oscillation Results

Super-K, atmospheric ν_μ

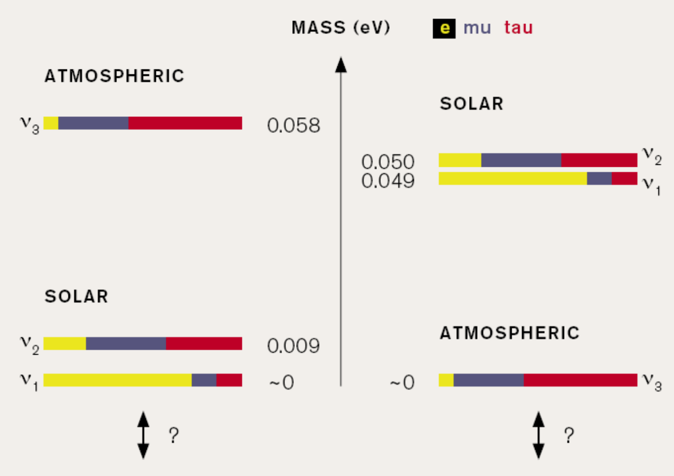


KamLAND, reactor $\bar{\nu}_e$



Clear wiggles!, different beat frequencies

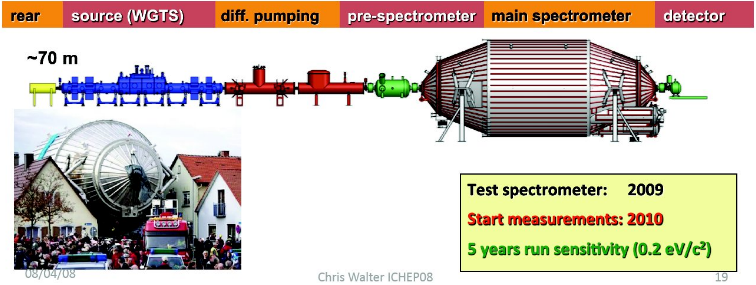
Neutrino Mass and Mixing

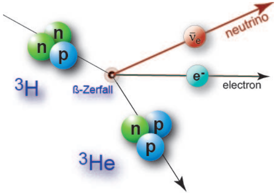


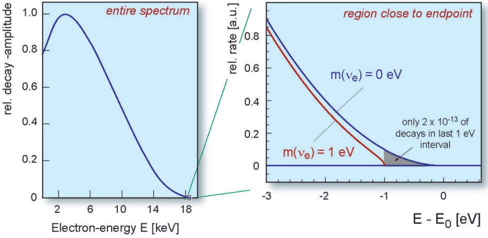
What is the *absolute* mass of the lowest mass state? OR How heavy is ν_e

Which is larger m_3 or m_1?

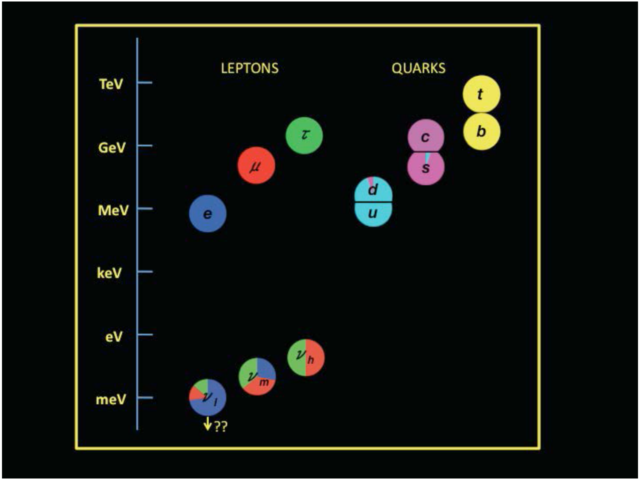
Measurement of the Absolute Neutrino Mass







Neutrino Mass Mysteries

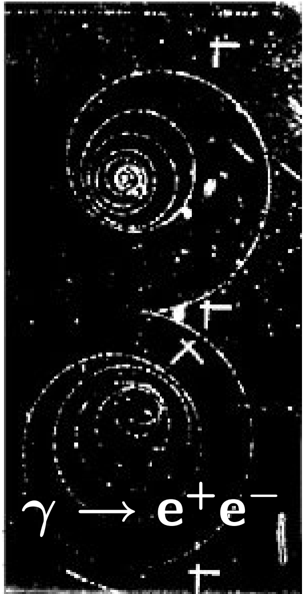


Why are neutrino masses so small??

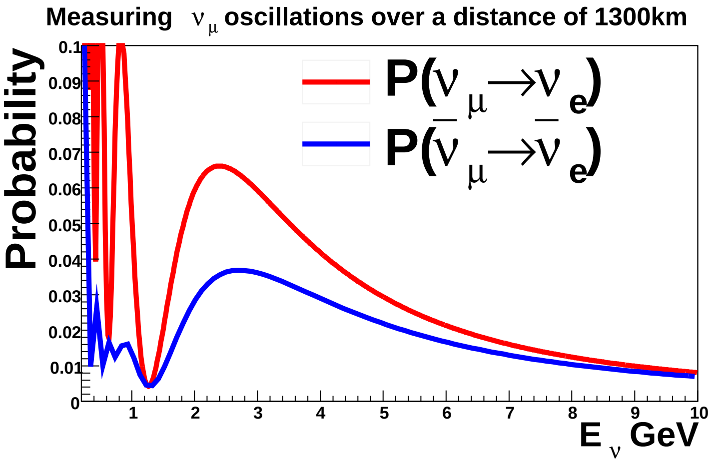
Charge-Parity Symmetry

Charge-parity symmetry: **laws of physics are the same if a particle is interchanged with its anti-particle and left and right are swapped.**

A violation of CP $\Rightarrow$ matter/anti-matter asymmetry.



Could neutrinos and anti-neutrinos oscillate differently?

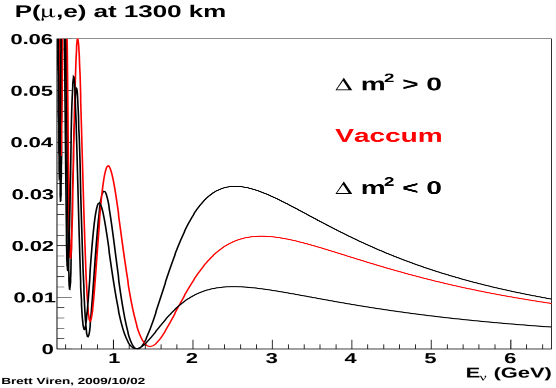


Could this explain the excess of matter in the Universe?

Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter acts as a refrective index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.

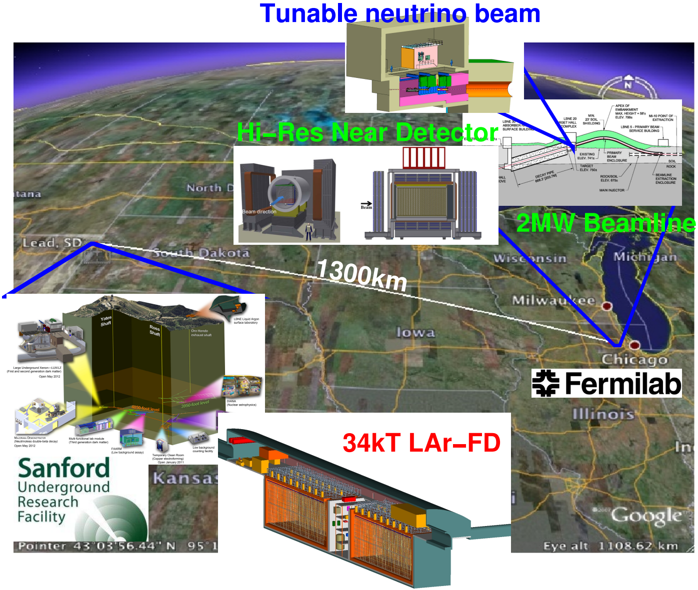
For $P_{osc} = P(\nu_\mu \rightarrow \nu_e)$:



We can determine the mass ordering using $\nu_\mu \rightarrow \nu_e$ oscillations

The Long Baseline Neutrino Oscillation Experiment

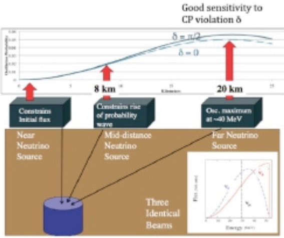
Measuring the mass ordering and $\nu/\bar{\nu}$ oscillation patterns.

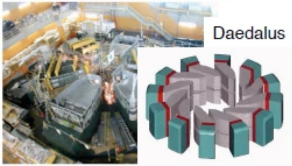


Practical Applications of Neutrinos

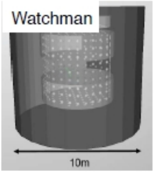
Synergies and Applications - Examples

Cyclotrons for neutrino physics (and industrial applications)





Neutrino detectors for reactor monitoring and non-proliferation



remote discovery of undeclared nuclear reactors with large detectors at km scale

US Short-Baseline Experiment

reactor antineutrino studies at short baselines

Summary

We know there are 3 known neutrino flavors with non-zero mass that mix.

BUT- what we dont know is even more important:

- **What is the absolute mass of ν_e? Why is it so much smaller than the mass of other elementary particles such as quarks?**
- **What is the mass ordering i.e is $m_1 > m_3$? What fundamental symmetry of nature is responsible for this mass ordering?**
- **Are neutrinos responsible for the matter/anti-matter asymmetry in the Universe?**
- **Are there only 3 neutrinos?**
- **What are the practical applications of neutrino physics?**

Lots of fun and challenges ahead.